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Abstract

This report presents the results of an investigation to use viscous computational fluid dynamic calculations to predict the flowfield and aerodynamic coefficients for a missile with grid fins in the supersonic flow regime. The calculations were made at Mach 2 and 3 and several angles of attack. The results were validated by comparing the computed aerodynamic coefficients against wind tunnel experimental data. Good agreement was found between the computed and experimental axial force coefficients, with the difference between 4 and 8%. Reasonable agreement was found for the normal force coefficient, with a difference of 8-16%. The agreement between the computed and experimental pitching moment coefficient was not as good, with a difference of 16-27%. Good agreement was found for the location of the center of pressure, with a difference of 6-10%. The flowfield around the individual grid fins and the normal force on the fins showed characteristics similar to those found in an earlier study.

VISCOUS CFD CALCULATIONS OF GRID FIN MISSILE AERODYNAMICS IN THE SUPERSONIC FLOW REGIME

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Abstract

This paper presents the results of an investigation to use viscous computational fluid dynamic calculations to predict the flowfield and aerodynamic coefficients for a missile with grid fins in the supersonic flow regime. The calculations were made at Mach 2 and 3 and several angles of attack. The results were validated by comparing the computed aerodynamic coefficients against wind tunnel experimental data. Good agreement was found between the computed and experimental axial force coefficients, with the difference between 4 and 8%. Reasonable agreement was found for the normal force coefficient, with a difference of 8–16%. The agreement between the computed and experimental pitching moment coefficient was not as good, with a difference of 16–27%. Good agreement was found for the location of the center of pressure, with a difference of 6–10%. The flowfield around the individual grid fins and the normal force on the fins showed characteristics similar to those found in an earlier study.

Introduction

A grid fin, also known as a lattice control, is an unconventional lifting and control surface that consists of an outer frame supporting an inner grid of intersecting planar surfaces of small chord. Interest in grid fins is primarily in their potential use on highly maneuverable munitions due to their advantages over conventional planar controls at high angles of attack (α) and high Mach numbers. The fin design offers favorable lift characteristics at a high α and near-zero hinge moments, which allows the use of small and lightweight actuators.¹⁻⁶

The available data on grid fins are based on wind tunnel tests,^{3,4,7} free-flight aeroballistic range tests,^{8,9} and numerical and theoretical investigations.¹⁰⁻¹⁵ The inviscid computational fluid dynamic (CFD)

computations of Sun and Khalid¹² showed reasonable agreement of the fin normal force with experimental data from Washington and Miller.¹ The inviscid computations of Chen *et al.*¹³ concentrated on the flow in the region of grid fin while studying the effect of a fairing ahead of the base of the fin. These investigations were performed in the supersonic regime, at Mach numbers of 1.5 to 2.5.

The viscous CFD computations of DeSpirito *et al.*^{14,15} showed very good agreement with the aerodynamic coefficients measured in wind tunnel tests of a 13-caliber generic missile tested at the Defence Evaluation and Research Agency (DERA), United Kingdom.^{3,4} Simulations of this model were performed at Mach 2.5 and several angles of attack between 0° and 20°. The normal force and pitching moment coefficients were calculated to within 7% of the measured data. The axial force was within 11% at 0° and within 6% at higher angles of attack. The normal force coefficients on the individual grid fins were calculated to within 10% of the measured data. A nonlinear variation of the normal force on the leeward grid fins with angle of attack was also captured.

The capability to perform viscous simulations in the supersonic flow regime was demonstrated on the DERA 13-caliber generic missile.^{14,15} The objective of the present study was to use that methodology to predict the aerodynamic coefficients on a 16-caliber missile shape representative of an air-to-air missile. The missile design was supplied by DERA, where research was aimed at investigating what advantages grid fins offered over conventional controls when employed on highly maneuverable air-to-air missiles.³ Calculations were performed at two Mach numbers, 2 and 3, and at several angles of attack at freestream conditions determined from wind tunnel tests performed concurrently at the Defence Research Establishment, Valcartier (DREV), Canada.⁷ This paper presents the results of these calculations and their validation against DREV wind tunnel data.

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Approach

Steady-state calculations were performed at two Mach numbers, 2 and 3, and at several angles of attack: 0°, 5°, 10°, and 20°. For the Mach 2 case, the freestream conditions were a Reynolds number (based on missile diameter) of 3.84×10^5 , a static temperature of 166 K, and a static pressure of 1.268×10^4 Pa. For the Mach 3 case, the freestream Reynolds number was 2.34×10^5 , the static temperature was 107 K, and the static pressure was 2.77×10^3 Pa. The model reference diameter (D) was 30 mm. The tail-controlled, air-to-air missile (TCAAM) configuration, shown in Figure 1a, consisted of a 3-caliber tangent ogive on a 13-caliber cylindrical body. The four grid fins were located 1.5 calibers ($1.5D$) from the rear of the missile. The grid fin, Figure 1b, had a span of $0.75D$, a height of $0.333D$, and a chord of $0.118D$. The simulations were performed with the missile in the cruciform (+) configuration, and symmetry (x - z plane) was used so that only a half plane was modeled. The DREV wind tunnel data ranged from -12° to $+12^\circ$ angle of attack. The $\alpha = 20^\circ$ angle of attack simulation was performed to compare with the previous grid fin CFD investigation.^{14,15}

The commercial CFD code, FLUENT, Version 5.3, was used for this investigation.¹⁶ The implicit, compressible (coupled), unstructured-grid solver was used. The three-dimensional, time-dependent Reynolds-averaged Navier-Stokes (RANS) equations are solved using the finite volume method:

$$\frac{\partial}{\partial t} \int_V W dV + \oint [F - G] \cdot dA = \int_V H dV,$$

where W is the vector of conservative variables, and F and G are the inviscid and viscous flux vectors, respectively, defined as

$$W = \begin{Bmatrix} \rho \\ \rho u \\ \rho v \\ \rho w \\ \rho E \end{Bmatrix}, \quad F = \begin{Bmatrix} \rho v \\ \rho v u + p i \\ \rho v v + p j \\ \rho v w + p k \\ \rho v E + p v \end{Bmatrix}, \quad G = \begin{Bmatrix} 0 \\ \tau_{xi} \\ \tau_{yi} \\ \tau_{zi} \\ \tau_{ij} v_j + q \end{Bmatrix}.$$

H is the vector of source terms, V is the cell volume, and A is the surface area of the cell face. The inviscid flux vector, F , is evaluated by a standard upwind flux-difference splitting. The Spalart-Allmaras¹⁷ one-equation turbulence model was used for these

calculations. In FLUENT, the original version of the Spalart-Allmaras model is modified to allow the use of wall functions when the mesh resolution is not sufficiently fine to resolve the viscous-affected, near-wall region of the boundary layer. This capability was used in generating the mesh so that the computational requirements were reduced as much as possible. Second-order upwind discretization was used for the flow variables and the turbulent viscosity equation.

The geometry and unstructured mesh were generated using the preprocessor GAMBIT, which is part of the FLUENT software suite. In generating the meshes, boundary layer mesh spacing was used near the missile body and fin surfaces. Advantage was taken of the wall function option of the solver in FLUENT, and the first point off the surface (cell center) was between 0.004 and 0.006 calibers from the surface. All mesh stretching was kept below 1.25. Hexahedral cells were used except for in a small region ahead of and partly over the first 0.1 calibers of the nose of the missile (less than 1% of the total length). The latter region was made up of tetrahedrons and pyramid transition elements. Figure 2 shows the mesh on the symmetry plane. The triangular surface mesh can be observed at the upstream end. The tetrahedral mesh was made to cover a small part of the missile nose only to allow a transition between the two types of meshes near the nose. Following the methodology established earlier,^{14,15} a nonconformal mesh interface was used at 13 calibers from the missile nose. This reduced the size of the mesh by eliminating the need to carry the complex, dense mesh near the fins into the missile forebody region. A true hybrid mesh with quadrilateral or prism elements in a layer around the solid surfaces and tetrahedral elements in the freestream was not attempted because of the difficulty in generating this mesh around the fins. The total number of cells in this mesh was about 3.9 million, with 3.2 million in the fin region (13–16 calibers). The mesh in the fin region is shown in Figure 3. The number of cells across the front and rear of the grid fin web and frame surface was one or two due to difficulty in meshing this small (0.14 mm, or $0.005D$) thickness. This dimension is the same order of magnitude as the first cell spacing off the surface.

The base flow was not simulated in these calculations, so the mesh ended at the end of the missile. An outflow boundary condition was used downstream, a pressure inflow (with freestream conditions) boundary condition was used upstream,

and a far-field pressure (nonreflecting) boundary condition was used for the outer boundary. A nonslip wall boundary condition was used for all solid surfaces. The y^+ value on the missile body was between 17 and 45 for the Mach 2 case, and about 7–30 for the Mach 3 case. The y^+ value was between 17 and 35 on the fin surfaces. The optimum y^+ value for wall functions is about 30–60 to ensure that the first point is in the log layer region of the boundary layer, rather than in the viscous layer. The y^+ values for the Mach 3 case are lower than optimum. It was not originally planned to perform the Mach 3 case in this study, so the same mesh used for the Mach 2 case was used. We believe that any inaccuracy in the turbulence model assumptions resulting from the lower than optimum y^+ value will not have a large effect on the aerodynamic coefficients.

The simulations were performed in parallel using six processors on a Silicon Graphics, Inc. (SGI) Origin 2000 with R12000 processors. The simulations were run with a CFL number between 2 and 4, with the lower value used for the first 200 iterations. The calculations took about 4–6 minutes per iteration using six processors. The aerodynamic coefficients converged in about 600–800 iterations, and it took about 1,200 iterations for the turbulent viscosity to converge, with a reduction in the scaled residual to about 5×10^{-5} .

Results and Discussion

Aerodynamic Coefficients

Using the FLUENT postprocessor, the viscous and pressure forces were integrated along the missile body and fin surfaces to calculate the aerodynamic coefficients. The normal force (C_n), axial force (C_x), and pitching moment (C_m) coefficients are presented in missile-based coordinates, with the origin located at the nose. The x -axis is aligned with the missile axis, and the z -axis is the vertical axis. The pitching moment is expressed about the nose of the missile. The reference area is the cross-sectional area of the missile base, and the reference length is the diameter of the missile.

The calculated aerodynamic coefficients are compared to the DREV wind tunnel measurements⁷ in Figures 4–6 and Tables 1 and 2. The normal force coefficient results are shown in Figure 4. The difference between the calculated and measured values is 7.8% at $\alpha = 5^\circ$ and 16% at $\alpha = 10^\circ$ for the Mach 2 calculations. The difference is 15% at $\alpha = 5^\circ$

and 14% at $\alpha = 10^\circ$ for the Mach 3 calculations. The axial force coefficient results (Figure 5) show good agreement, with the difference between the calculated and measured values between 4% and 8% over the angle-of-attack range for both Mach numbers. The agreement of the pitching moment coefficient (Figure 6) is not as good, with a difference of about 16–27% between the calculated and measured values over the angle of attack range and Mach numbers investigated. Good agreement was found for the computed location of the center of pressure, x_{cp} , with a difference between 6% and 10%. The values at $\alpha = 0^\circ$ were not included in the above difference calculations because C_n and C_m are near zero. Interestingly, the CFD captured the nonlinearity in the C_n and C_m curves at Mach 3 that are present in the wind tunnel data.

Table 1. Calculated and Experimental Aerodynamic Coefficients and Center of Pressure at Mach 2.

α		C_n	C_m	C_x	x_{cp}
0	CFD	0.0001	0.0009	0.3993	9.00
	EXP	-0.0215	0.2687	0.4234	12.5
	diff.	-	-	-5.69%	-
5	CFD	0.6549	-6.3230	0.4096	9.65
	EXP	0.6078	-5.4667	0.4453	8.99
	diff.	+7.75%	-15.7%	-8.02%	+7.34%
10	CFD	1.4407	-12.8200	0.4149	8.90
	EXP	1.2411	-10.1029	0.4340	8.14
	diff.	+16.1%	-26.9%	-4.40%	+9.33%

Table 2. Calculated and Experimental Aerodynamic Coefficients and Center of Pressure at Mach 3.

α		C_n	C_m	C_x	x_{cp}
0	CFD	-0.0005	0.0073	0.4127	14.6
	EXP	-0.0112	0.0563	0.4448	5.03
	diff.	-	-	-7.22%	-
5	CFD	0.5748	-4.6125	0.4236	8.02
	EXP	0.5015	-3.6615	0.4619	7.30
	diff.	+14.6%	-26.0%	-8.29%	+9.86%
10	CFD	1.5453	-12.2338	0.4274	7.92
	EXP	1.3595	-10.1740	0.4568	7.48
	diff.	+13.7	-20.2%	-6.44%	+5.88%

The normal force coefficients on the individual grid fins are shown in Figure 7. The fins are

numbered 1–4, with Fin 1 in the 3 o'clock position and Fin 4 in the 12 o'clock position (if looking forward from the rear of the missile in the "+" configuration). In the simulations, Fin 1 and Fin 3 are the same due to symmetry. The forces on the fins were not measured in the DREV wind tunnel experiment, so no validation data are available. In the previous investigation^{14,15} there was excellent agreement between the calculated and measured fin normal force. The results for the present simulation show the same characteristics. The largest normal force is provided by the horizontal fins, as expected. The windward fin (bottom, Fin 2) also provided substantial normal force, about 50% of the horizontal fins. At Mach 2, the leeward fin (top, Fin 4) provides a similar normal force as Fin 2 up to about $\alpha = 5^\circ$. Above 5° , the normal force on the leeward fin decreases and becomes negative. At Mach 3, the normal force on the leeward fin does not increase as α increases, but begins to decrease at about $\alpha = 5^\circ$, as in the Mach 2 case. As discussed by Simpson,³ the nonlinear shape of the normal force vs. α curve for the leeward fin is due to its location in the separated flow region. As shown later in plots of the flowfield, the local angle of attack varies over the leeward fin. Some parts are at an effective negative angle of attack, while other parts are at an effective positive angle of attack.

The difference between the measured and calculated C_m was surprising. The previous study of the DERA 13-caliber generic missile demonstrated that the current meshing and solution methodology could give very good results.^{14,15} Figure 8 shows the results of those calculations, which were performed at Mach 2.5 at several angles of attack and were validated with DERA wind tunnel measurements. The aerodynamic coefficients of the missile were calculated to within 6–11% of the measured data, and the normal force on the grid fins was calculated to within 10%. The capturing of the nonlinear effect on the leeward fin indicated that the flow separation region was calculated with reasonable accuracy.

Several potential explanations for the difference in the C_m are considered. One possibility is that the location of the separation on the leeside of the missile was not calculated correctly. To investigate this, several simulations of the TCAAM body with no fins were performed and compared against data from an earlier study.¹⁸ Experimental data was not available for the conditions used in our study, so the comparison was made at Mach 2.5 and $\alpha = 14^\circ$. Figure 9 shows the azimuthal pressure coefficient

(C_p) distribution at four axial locations, $x/d = 3.5, 6.5, 7.5$, and 9.5 . The calculations were performed at the same Reynolds number, 1.23×10^6 , as in the earlier study.¹⁸ The results at an x/d of 3.5 and 9.5 agree reasonably well. The results at an x/d of 6.5 and 7.5 are not as good, but are consistent with the results of the CFD codes investigated in the previous study.¹⁸ The previous study also found that even with some discrepancies in predicting the separation point, the aerodynamic force and moment predictions were accurate to within 5%. Similarly, the present study of the TCAAM body alone predicted the aerodynamic coefficients to within 3% and x_{cp} to within less than 1.5%. It is therefore unlikely that the large difference in C_m for the grid fin calculations are due to an inaccuracy in the prediction of the flow separation on the leeside of the missile.

A second possible explanation could be an error in the calculation of the forces on the grid fins. Since there is no measured force data to validate against, it is impossible to be sure. However, there is some confidence in the fin normal force data since it was so accurately predicted in the study of the DERA generic missile,^{14,15} and the correct trends were observed in the TCAAM calculation (Figure 7).

Another possible explanation is an error in the wind tunnel data. In the DREV wind tunnel measurements, the model is swept from -12° to $+12^\circ$ angle of attack during the 6-s test run time.¹⁹ It was recently proposed²⁰ that a dynamic effect due to grid fins may exist. This was considered a possible explanation for a sharp change in x_{cp} in the low transonic range observed in aeroballistic range tests.⁹ This effect was not previously observed in wind tunnel tests, which are relatively static compared to aeroballistic tests. If there is a dynamic effect due to grid fins, it may be possible that the sweep rate, $4^\circ/\text{s}$, in the DREV wind tunnel tests is fast enough to cause this effect. This is purely speculative at this time, and further investigation is warranted. Static wind tunnel tests at several angles of attack are planned at DREV.¹⁹ The model was also swept in wind tunnel measurements performed at DERA,^{3,4} but the sweep rate was not reported. It is expected that the sweep rate is lower than that in the DREV wind tunnel since it is a continuous run tunnel, as opposed to the blow-down tunnel at DREV.⁷

Although grid fins have been investigated experimentally for over a decade, the CFD prediction of grid fin missile flows has only recently been undertaken.^{11–15} All the effects specific to these novel

control devices are not fully understood and further investigation, numerical and experimental, needs to be done.

Grid Fin Flowfield

Contour plots of C_p on the symmetry plane are shown for the Mach 2, $\alpha = 10^\circ$ case in Figure 10. A strong oblique shock is emanating from the windward side of the nose, with a weaker shock coming off the leeward side. An expansion fan is emanating from the ogive-body interface, and a separated flow region on the leeward side begins at one-third of the body length from the nose. Figure 10b shows a close-up of the complex, three-dimensional shock structure in the fin region. Figures 11a and 11b show the C_p contours on the symmetry plane through the leeward and windward fins, respectively. On the top fin (Figure 11a), the top cell is nearly at zero angle of attack, with a shock wave on the top and bottom of the cell. The other cells are at an effective negative angle of attack, with a shock wave on the bottom of the cell and expansion over the top part of the cell. This illustrated the phenomenon discussed earlier and is due to the recirculating flow from the separation on the leeward side of the missile. The entire bottom fin (Figure 11b) is at an effective positive angle of attack.

The flow around the missile is further illustrated in Figure 12, which shows pressure coefficient contours at several axial stations along the missile body. At 3 calibers, the ogive-body interface, the flow has not separated. At 8 calibers, the flow has separated and the two vortices on the leeward side of the body can be clearly seen. These vortices are well developed by 14 calibers, which is just ahead of the fins. At the base of the missile, 16 calibers, the effect of the interaction with the leeward fin is nearly complete. The effect of the shock interactions with the horizontal fins is also observed.

Summary and Conclusions

Calculations of the viscous flow over a tail-controlled missile with grid fins in the supersonic flow regime were made using CFD. The calculations were made at Mach 2 and 3 and several angles of attack. The results were validated by comparing the computed aerodynamic coefficients against wind tunnel experimental data.

Good agreement was found between the computed and experimental axial force coefficient, with a difference of 4–8%. Reasonable agreement was found for the normal force coefficient, with a

difference of 8–16%. The agreement of the pitching moment coefficient was not as good, with a difference of 16–27% between the calculations and the experimental data. Good agreement was found for the location of the center of pressure, with a difference of 6–10%.

The normal forces on the individual grid fins showed similar characteristics to those observed in a previous study.^{14,15} The normal force on the leeward fin decreased as the angle of attack increased above 5° and subsequently went negative. This phenomenon was illustrated in C_p contours around the leeward grid fin, which showed that the effective angle of attack was negative on most of that fin.

The reason for the discrepancy between the calculated and measured pitching moment coefficient is unknown. Possible explanations for inaccuracies in both the numerical and experimental data were put forward, but further investigation is needed.

Acknowledgments

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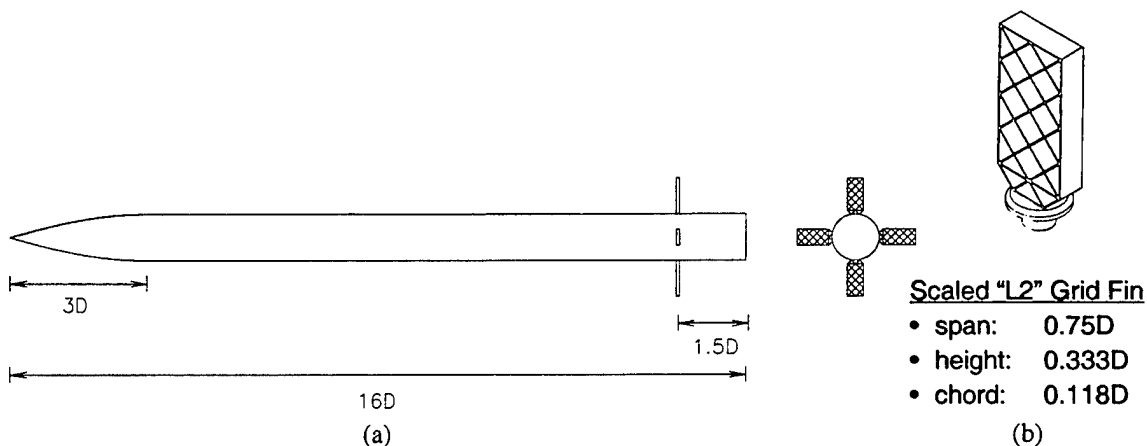


Figure 1. Tail-Controlled Missile (a) and Grid Fin (b).

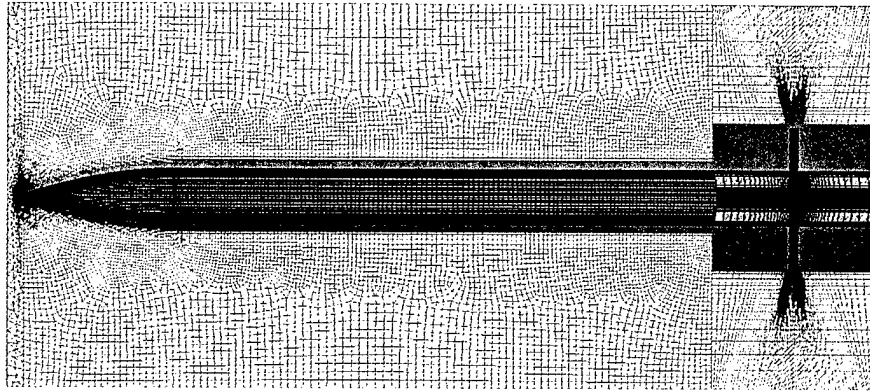


Figure 2. Mesh on Symmetry Plane.

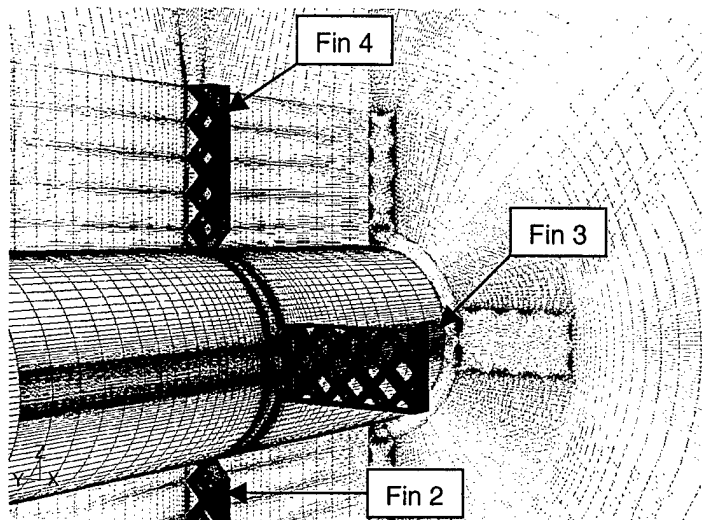


Figure 3. Mesh in Fin Region.

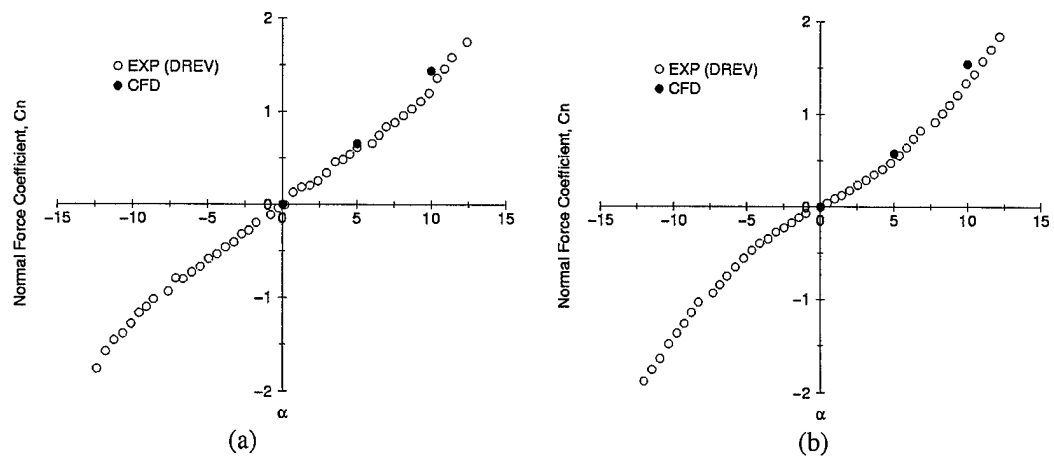


Figure 4. Comparison of CFD (Filled Circle) With DREV Experiment (Circle): Normal Force Coefficient at (a) Mach 2 and (b) Mach 3.

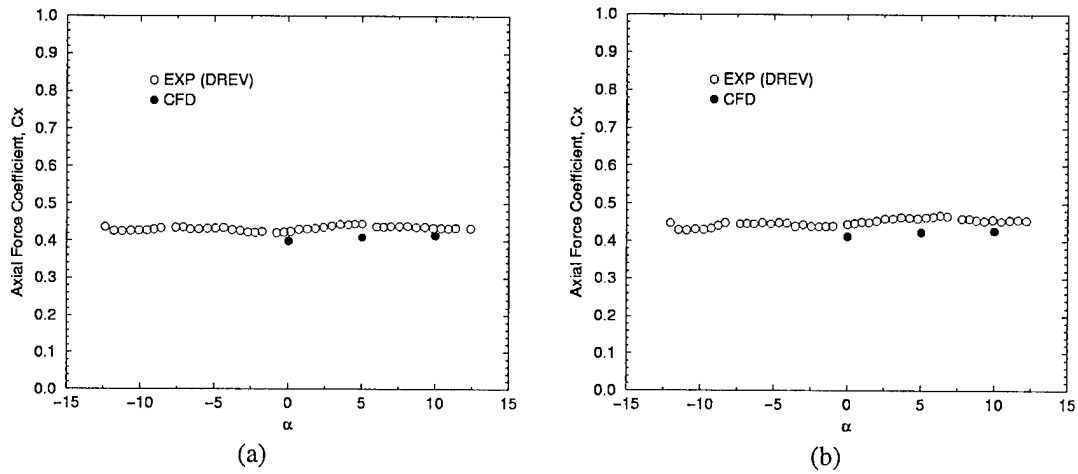


Figure 5. Comparison of CFD (Filled Circle) With DREV Experiment (Circle): Axial Force Coefficient at (a) Mach 2 and (b) Mach 3.

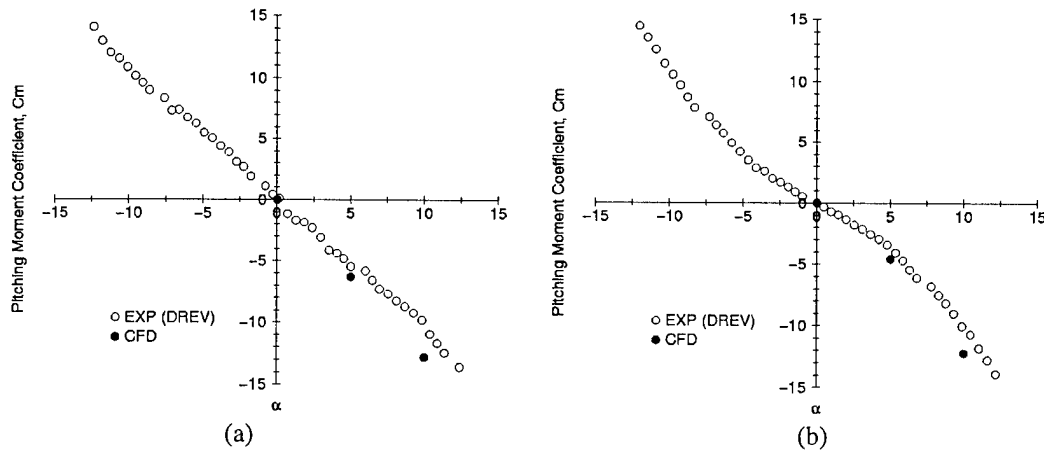


Figure 6. Comparison of CFD (Filled Circle) With DREV Experiment (Circle): Pitching Moment Coefficient at (a) Mach 2 and (b) Mach 3.

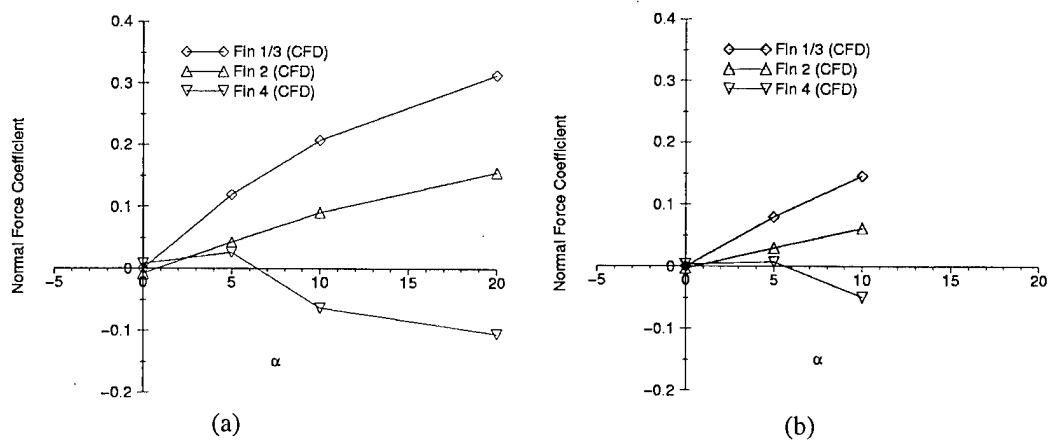


Figure 7. Normal Force Coefficient on Individual Grid Fins at (a) Mach 2 and (b) Mach 3.

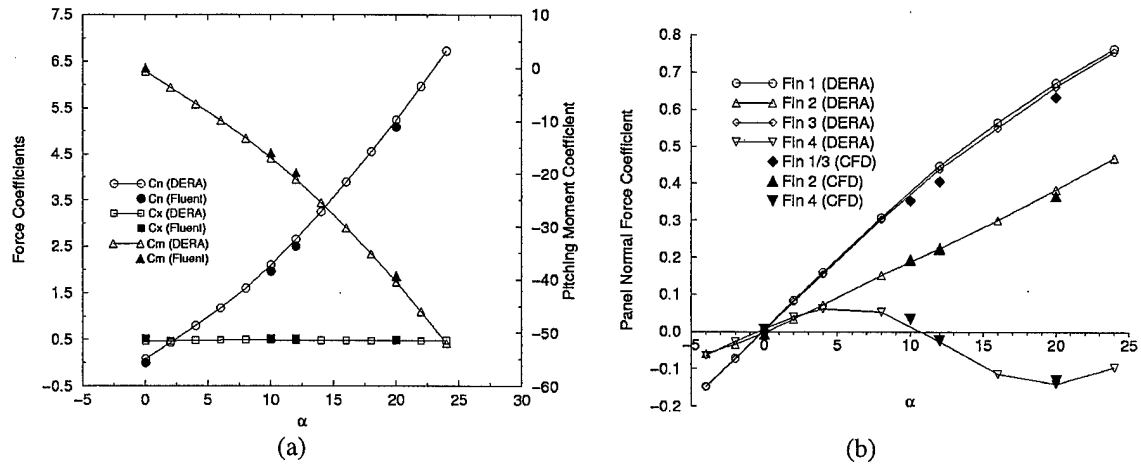


Figure 8. Experimental and Calculated Aerodynamic Coefficients on DERA Generic Missile: (a) C_n , C_x , and C_m on Missile and (b) C_n on Fins.

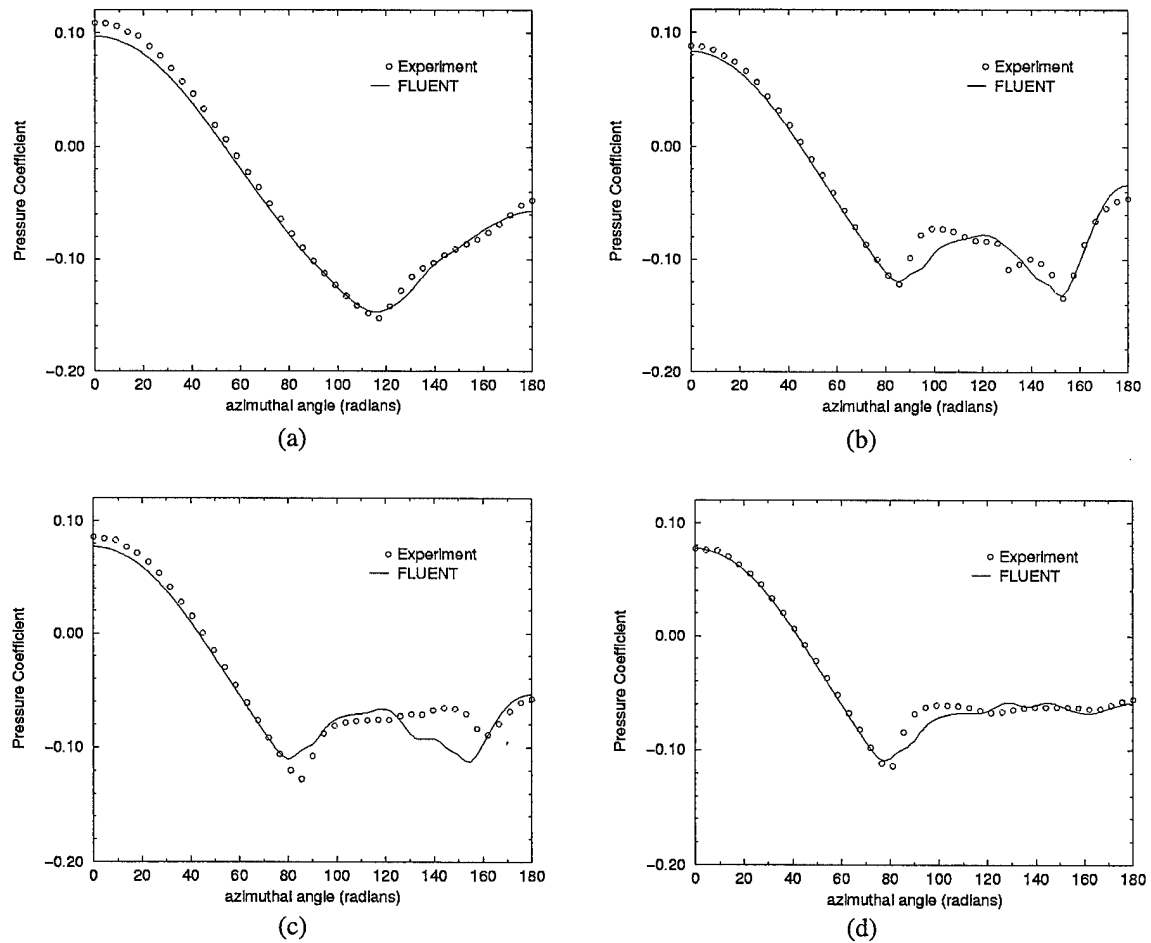


Figure 9. Pressure Coefficient on Surface of Missile Body at x/d of (a) 3.5, (b) 6.5, (c) 7.5, and (d) 9.5 for Mach 2.5, $\alpha = 14^\circ$, and $Re = 1.23 \times 10^6$.

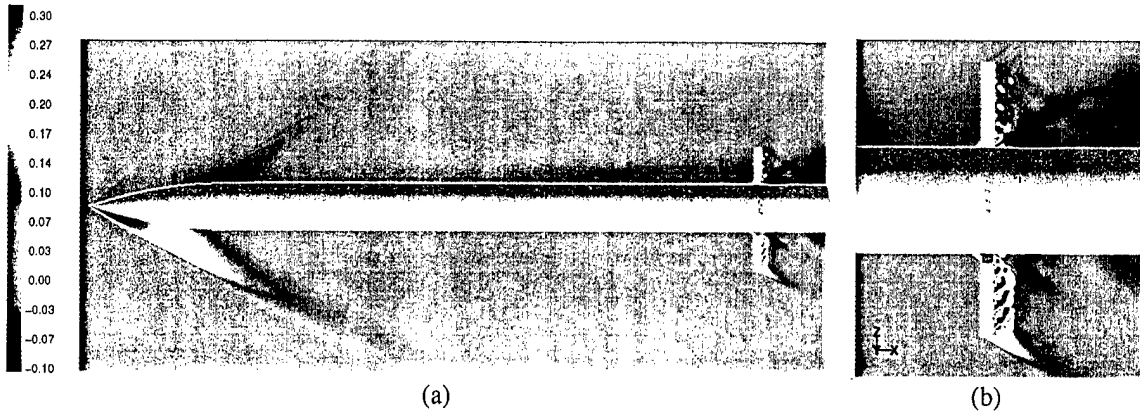


Figure 10. Pressure Coefficient Contours on Symmetry Plane at $\alpha=10^\circ$, Mach 2: (a) Flow Over Missile; (b) Flow in Fin Region.

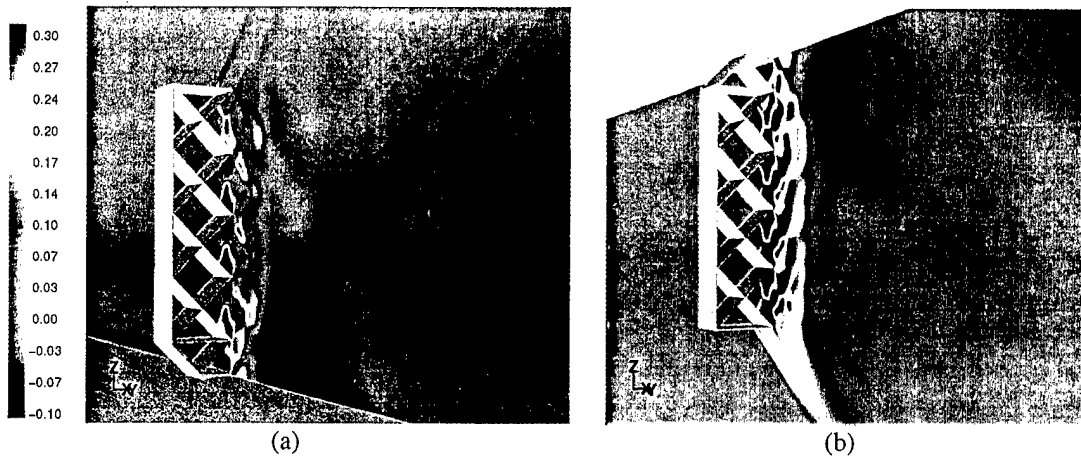


Figure 11. Pressure Coefficient Contours on Symmetry Plane Through (a) Fin 4 and (b) Fin 2 at $\alpha=10^\circ$, Mach 2.

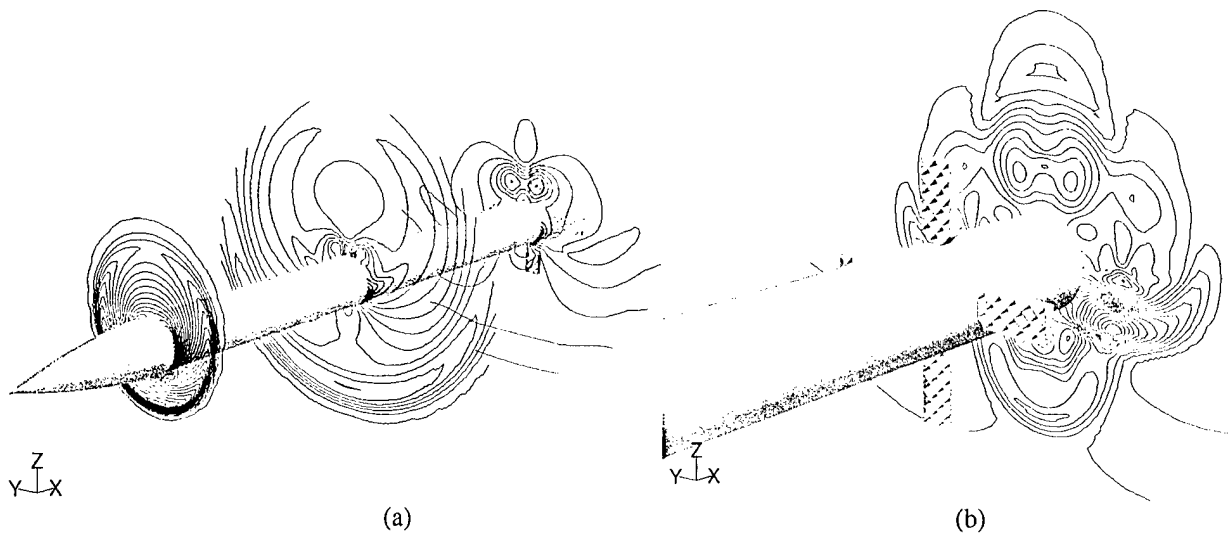


Figure 12. Pressure Coefficient Contours on Axial Planes (x/d) Located at (a) 3, 8, 14, and (b) 16 Calibers For Mach 3, $\alpha=10^\circ$ Case.

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13. ABSTRACT (Maximum 200 words) This report presents the results of an investigation to use viscous computational fluid dynamic calculations to predict the flowfield and aerodynamic coefficients for a missile with grid fins in the supersonic flow regime. The calculations were made at Mach 2 and 3 and several angles of attack. The results were validated by comparing the computed aerodynamic coefficients against wind tunnel experimental data. Good agreement was found between the computed and experimental axial force coefficients, with the difference between 4 and 8%. Reasonable agreement was found for the normal force coefficient, with a difference of 8-16%. The agreement between the computed and experimental pitching moment coefficient was not as good, with a difference of 16-27%. Good agreement was found for the location of the center of pressure, with a difference of 6-10%. The flowfield around the individual grid fins and the normal force on the fins showed characteristics similar to those found in an earlier study.				
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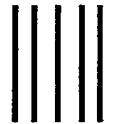
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